



Using Cyanex 923 for selective extraction in a high concentration chloride medium on nickel metal hydride battery waste

Part II: mixer–settler experiments

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ABSTRACT

Nickel metal hydride batteries are extensively used throughout society and represent a large and complex metallic mixture requiring recycling. This paper deals with the recovery and separation of metals from nickel metal hydride battery waste dissolved in 8 M hydrochloric acid. Three processes based on leachates from individual electrode materials and a mixed material have been evaluated using mixer–settlers. The solvating extractant used is the trialkylphosphine oxide mixture Cyanex 923. The batteries used in this study contained thirteen metals and the processes separate them in up to four fractions. The main fraction in each process successfully creates a high-concentration nickel stream with low levels of potassium and magnesium (if present in the feed) by extracting the other metals. The purity of the nickel stream after the main process step (4–5 stages) is >99.9%, excluding magnesium and potassium. The extracted metals are separated using a nitrate strip, which allows the rare earth metals and aluminium to be separated from cobalt and manganese.

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1. Introduction

The use of nickel metal hydride (NiMH) batteries is extensive in society today, e.g. in hybrid electric vehicles. The amount of valuable metals used in their construction is significant. This means that effective and robust processes for material recovery are and will be needed for the recycling of NiMH batteries. Several processes using liquid–liquid extraction for the recycling of NiMH batteries have been suggested in literature, e.g. by Zhang et al. (1998, 1999), Tzanetakis and Scott (2004), and Li et al. (2009). Commonly these processes use acidic extractants such as D2EHPA or Cyanex 272. The aqueous solutions of dissolved batteries are often created by using approximately 1–4 M sulphuric or hydrochloric acid. However, in a previous study (Larsson et al., 2012) a new approach to this recycling was suggested by using a much more concentrated system to reduce aqueous volumes and thereby improving the efficiency of processes by reducing the size of treatment plants. To purify the nickel a solvating extractant (Cyanex 923) is used to extract metals other than nickel in a single step. The current study focuses on the further development of this process and testing in mixer–settlers for the purpose of showing the feasibility of the process.

2. Background

The solid waste has been divided into three fractions during mechanical separation, creating three individual processes. The three different feed materials with corresponding separation routes are equivalent to two different cases of dismantling of the batteries, the first case involving the cathode and anode active materials being separated and the second case involving shredding of the electrode plates to make a mixed material fraction. A small mixed material fraction is probably unavoidable in the case of individual electrode material separation. The benefit of physically separating the electrode materials is that the composition of the two materials is different and the metal separations are simpler than for a mixed system.

The concentration of the hydrochloric acid used for dissolution is crucial with respect to the volume of aqueous phase, which in turn is related to the required organic volume. Minimizing volumes reduces the required flow size in a treatment plant thereby reducing the plant's size and cost. For this process the volume is kept low by means of high concentrations and selective leaching. Using non-oxidizing conditions for dissolution of cathode electrodes or mixed material can prevent the dissolution of nickel metal. For the batteries used in this study this reduces the acid consumption and corresponding flow size for cathode material by 37% and the corresponding amount for the mixed material (Larsson et al., in press).

During dissolution almost all of the hydrogen ions are consumed, and the metal concentration at the end of dissolution is equivalent

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to the acid strength divided by the average oxidation number of the dissolved metals. This means a smaller volume is required for dissolution than in more dilute systems or systems with a higher acidity at the end of the dissolution. In these experiments 8 M hydrochloric acid is used, since a high chloride concentration allows for sufficiently high distribution ratios when using Cyanex 923. At this concentration the metals also stay dissolved in solution, whereas at higher chloride concentrations there is a risk of precipitation.

The approach of using systems with a high metal concentration is particularly appropriate in recycling applications, as a reduced flow size means more efficient processes (reduced energy and chemical usage) combined with a smaller start-up cost related to constructing a plant. In certain cases this additional reduction can mean that a demonstration-size plant can be sufficient to treat a particular waste product requiring recycling, since such wastes can often be low in volume but high in value.

The primary purpose in choosing a solvating extractant, Cyanex 923, for group extractions in a process treating dissolved nickel metal hydride battery waste is that this step can simply and robustly purify the nickel content and requires no pH control during extraction. The 10 metals other than nickel, magnesium and potassium are effectively extracted if the acidity is kept low, since high acidity reduces the distribution ratio of lanthanoids and aluminium. This main extraction step purifies the nickel with respect to these other metals and can allow for either direct electrowinning or further purification if the magnesium or potassium requires removal. It should be pointed out that for a sufficiently washed anode material neither magnesium nor potassium is present, and the nickel is pure after the initial separation.

3. Experimental

The used battery materials were from Panasonic prismatic module 6.5 Ah NiMH plastic casing batteries used in a hybrid electric vehicle. The solid materials were dissolved using 8 M hydrochloric acid (Acros, reagent grade). All dilutions were prepared using pure water (MilliQ, Millipore, > 18 MΩ/cm).

Three different types of solutions used as water phases were made by dissolving anode material, cathode material and a mixed electrode material. The mixed material was made by shredding whole cells and subsequently removing the whole separators and anode backing material (nickel-plated steel), which remained intact during the shredding.

For the organic phases Cyanex 923 (95%, Cytec), tributyl phosphate (97%, Aldrich), 1-decanol (99%, Aldrich) and aliphatic kerosene distilled at 190–250 °C (Solvent 70, Statoil) were used. In order to improve phase separation and inhibit third-phase formation, compared to the process layouts suggested in the previous article (Larsson et al., 2012) using this system, a modification was introduced in that 10% of 1-decanol was added to the high extractant concentration solvents. This makes the organic solvents for the main extractions consist of 70% Cyanex 923, 10% Solvent 70, 10% TBP and 10% 1-decanol.

For the anode and mixed materials an increased percentage of nickel in the aqueous solutions is achieved by refluxing part of the purified nickel stream; thereby increasing the concentration of chloride at the end of extraction, allowing for higher distribution ratios. The reflux was simulated using 4 M nickel chloride solutions, prepared using hexahydrate nickel(II) chloride (97%, Acros).

The experiments were performed using lab-scale mixer-settlers in order to simulate an experimental pilot-plant set-up. The type of mixer-settler is described in a report by Liljenzin et al. (1980). The mixer-settlers are made of PVDF and have a counter-current flow scheme. Up to five stages were used in the mixer-settler separation steps. The different extraction steps in the process were performed individually, after which phases were collected for further separations. The settling chamber of the mixer-settler units has a volume

of approximately 120 ml, the volume of the mixing chamber is 30 ml and the length of the settling chamber is 7.5 cm. Samples were taken from the phases in the mixer-settler after 1 L or more had been pumped through the system, and this was generally sufficient to achieve near steady-state conditions.

3.1. Dissolution

Initially slightly less than the stoichiometric equivalent of the necessary amount of protons for dissolution was added to the solid material. The amount of 8 M hydrochloric acid added was 3.75 ml per gram anode material, 1.96 ml per gram cathode material and 2.7 ml per gram mixed material. Nitrogen was bubbled through the solution for the cathode and mixed dissolutions to inhibit nickel metal dissolution. All dissolutions were initially cooled using ice baths, since the raised temperature in the cathode case can increase nickel metal dissolution, and in order to reduce the temperature of the anode dissolution so as to make the reaction less violent. When the dissolutions were visibly less reactive an automatic titration device (Mettrom 905 Titrando) controlled the final addition of 8 M acid to allow for a low acidity in the final solution. After this the solutions were filtrated, removing nickel metal for the cathode dissolution and organic material for the anode dissolution. Because of the high metal concentration the anode material was not fully dissolved in a single step. In a process this can be solved by using a simple two-step method whereby the 8 M hydrochloric acid is contacted with the residue material after the initial dissolution to leach the last metals, and this acid is subsequently added to the first step, schematically shown in Fig. 1. The resulting concentrations of the leach liquors after adding the simulated reflux levels are shown in Table 1.

3.2. Metal ion concentration analysis

A Thermo iCAP 6500 inductively coupled plasma optical emission spectrometer (ICP-OES) was used to determine metal concentrations in the samples. All samples were diluted using 1 M nitric acid diluted from concentrated (65%) nitric acid (Suprapur, Merck). Measurement uncertainties were estimated using triple samples.

The concentrations were represented using the logarithm of the molar concentration in order to give an overview of the concentration trends in the mixer-settlers. A common detection limit was set for the graphical representations at a concentration of 0.1 mM (giving a range of the logarithm values down to -4). Concentrations below this limit value were considered less relevant to a description of the behavioural trend, since several metals are close to detection limits at this concentration.

The stage numbers of the graphs of aqueous and organic concentrations are such that stage 1 is the aqueous inlet stage and consequently the organic outlet stage. Stage 0 is the aqueous feed concentration.

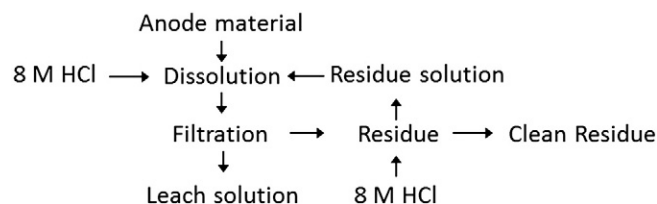


Fig. 1. Schematic description of the anode material dissolution. This increases the metal recovery, since the high metal concentrations initially prevent full dissolution.

Table 1

Molar concentrations of the three feed liquors and the percentage of total metal concentration. The simulated reflux level of 4 M nickel chloride has been added to the dissolved electrode materials: 50% for the anode material and 30% for the mixed material.

	Anode		Cathode		Mixed	
Al	0.08	2.1%	0.01	0.3%	0.05	1.4%
Ce	0.07	1.8%	nd		0.04	1.2%
Co	0.08	2.1%	0.44	11.4%	0.19	5.3%
Fe	0.004	0.1%	0.01	0.2%	0.007	0.2%
K	0.002	0.1%	0.04	1%	0.009	0.2%
La	0.20	5.2%	nd		0.14	3.7%
Mg	nd		0.09	2.3%	0.03	0.7%
Mn	0.13	3.4%	0.01	0.3%	0.10	2.7%
Nd	0.02	0.6%	nd		0.02	0.4%
Ni	3.2	84.1%	3.2	83.9%	3.1	85.3%
Pr	0.01	0.2%	nd		0.01	0.2%
Y	0.01	0.3%	0.05	1.2%	0.02	0.6%
Zn	nd		0.03	0.8%	0.01	0.3%

4. Results

4.1. Mixer-settler results for the cathode-based leach liquor

In the process based on dissolved cathode material, low-concentration Cyanex 923 extracts zinc and iron, followed by a high-concentration Cyanex 923 step removing aluminium, cobalt, manganese and yttrium. This leaves only nickel and low concentrations of potassium and magnesium in the aqueous phase. The cobalt and manganese can be stripped from the organic phase, either together with yttrium, using a hydrochloric acid strip, or separately, using a nitrate strip.

A deviation in the experiment from the extraction-process layout shown in Fig. 2 is that the acidic scrub from scrubbing the iron- and zinc-loaded solvent from the pre-main step is not returned to the

dissolution step and used for the dissolution. Instead the leach liquor is taken straight from dissolved active cathode material, and the aqueous solution after the zinc and iron extraction is used as is. This has the effect of slightly lowering the cobalt, manganese and yttrium concentration in the subsequent main extraction step. This should only have a minor effect on the results. Any lanthanoid trace contamination in the cathode material will follow the yttrium content.

The aqueous phase concentration of the first extraction is shown in Fig. 3. The initial conditions used in the experiment were not favourable for iron extraction, likely due to an incorrect acidity; to improve the iron extraction the extractant concentration can be raised or the acidity modified. More than 99.8% of the zinc content was extracted in four stages. For greater purity further stages can be added. A low percentage of yttrium (3.6%) and cobalt (9.3%) was extracted. This organic phase was scrubbed using 3 M hydrochloric acid. This scrubbed (>99%) the extracted cobalt and yttrium over three stages and can thereafter be returned to the dissolution step. Less than 5% of the zinc was scrubbed.

The aqueous phase concentration of the main extraction step is shown in Fig. 4. The extraction trend is that the metals other than nickel, magnesium and potassium are effectively extracted. Using molar concentrations the sum of the aluminium, cobalt, manganese and yttrium content represents less than 0.01% of the remaining aqueous phase metal concentration. Additional mixer-settler stages can be added to improve the purity without affecting nickel recovery, as can be seen from the constant nickel concentration in each stage. However, three stages or more likely give acceptable purity (>99%). The remaining metal content in the aqueous phase is nickel, with potassium and magnesium still present at less than 5%. The level of potassium is dependent on the washing at the mechanical separation stage.

The concentration in the organic phase is shown in Fig. 5. The concentration of magnesium and nickel is constant in stages 2–4 and

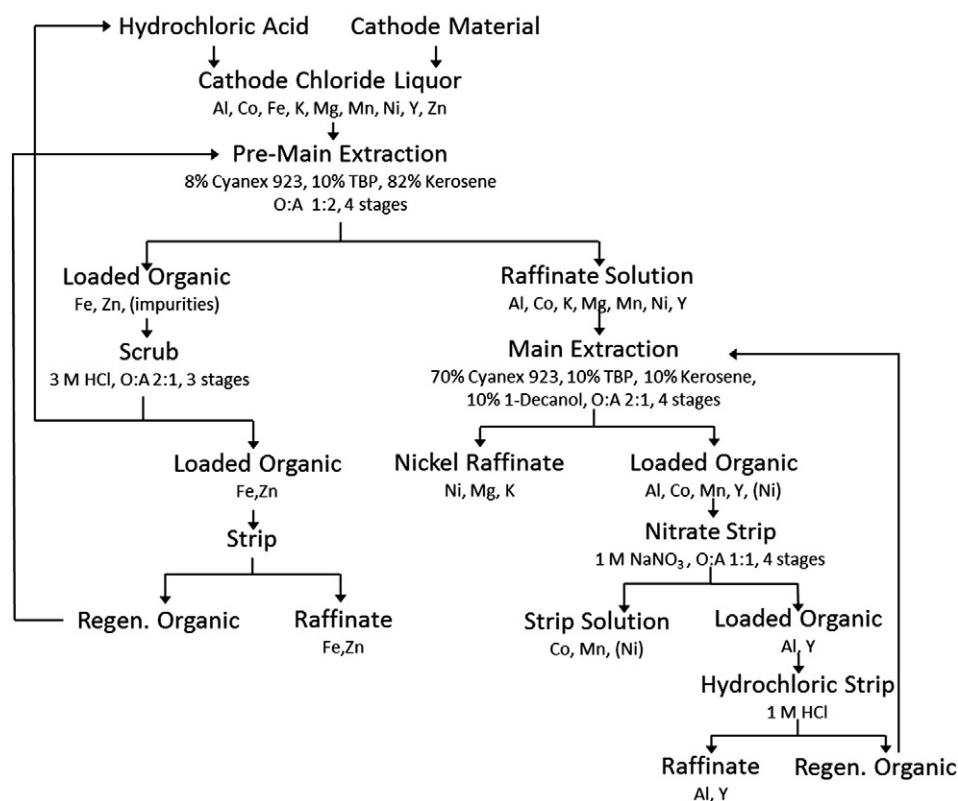


Fig. 2. Process layout for the cathode material. For each extraction there is an indication of the phase ratios of the flow rates and the number of stages used. Low levels of impurities are indicated in brackets.

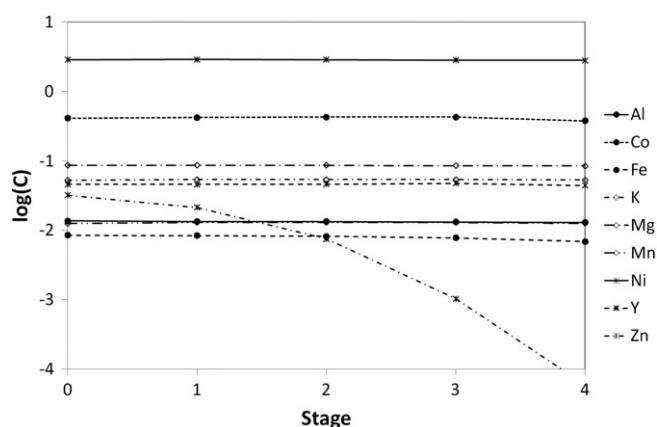


Fig. 3. Logarithm of aqueous molar concentration of the cathode pre-main extraction step, zinc and iron removal, four-stage experiment. Stage 0 is the aqueous phase before entry into the mixer-settler battery. The aqueous phase is the leach liquor based on the cathode electrode material, and the organic phase is 8% Cyanex 923 with a flow ratio of 1:2 (O:A).

significantly less in stage 1. This indicates that crowding affects the extraction. The extraction of cobalt manganese and yttrium thereby reduces the nickel and magnesium extraction. Optimizing flow rates to increase the cobalt, manganese and yttrium loading can further reduce the extraction of magnesium and nickel.

The organic phase was stripped using 1 M sodium nitrate. The aqueous concentrations are shown in Fig. 6. The manganese strip is incomplete, and this problem can be solved either by adding stages or by increasing the acidity by replacing part of the sodium nitrate with nitric acid. However, increasing the acidity will also lower the distribution ratios of yttrium and aluminium, and would thereby contaminate the cobalt and manganese stream.

The resulting organic phase was stripped with 1 M hydrochloric acid to remove yttrium and aluminium. Since the amount of yttrium and aluminium in the solid material was low the concentration in the aqueous strip phase was also low. This concentration can be raised, e.g. by recirculation of the aqueous strip or by using a higher phase ratio.

4.2. Mixer-settler results for the anode-based leach liquor

In the process based on dissolved anode material, high-concentration Cyanex 923 extracts cobalt, aluminium, manganese, lanthanum, cerium, neodymium, praseodymium and yttrium (and iron if present), shown in

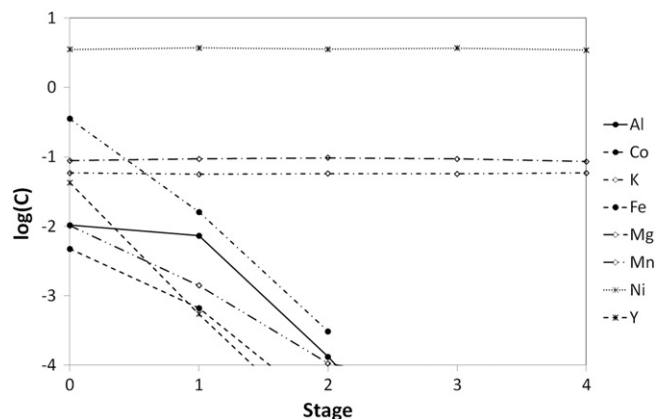


Fig. 4. Aqueous phase molar concentration of the main extraction with the leach liquor based on cathode material after zinc removal. Stage 0 is the aqueous phase before entry into the mixer-settler battery. The organic phase is 70% Cyanex 923. (O:A flow ratio 1:1).

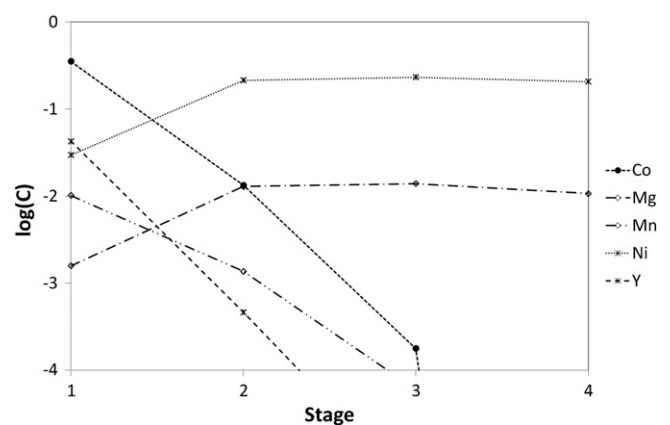


Fig. 5. Organic phase molar concentration of the main extraction with the leach liquor based on cathode material after zinc removal. Manganese, yttrium and cobalt concentration calculated by mass balance from aqueous concentration, assuming constant phase volume flow (O:A flow ratio 1:1). Nickel and magnesium concentrations are measured values.

Fig. 7. The purified aqueous phase subsequently only contains nickel (and potassium if the anode material was insufficiently washed).

A lower acidity was used than for the cathode process, as the lanthanoid extraction is inhibited by a high acidity. The potassium content was removed from the anode material by washing, so the concentration was very low. Care was also taken to minimize any iron in the process by carefully removing the anode active material from the electrode backing material (iron-rich).

The aqueous concentration of the main extraction is shown in Fig. 8. Similarly to the cathode process, the nickel and potassium contents remain approximately constant. The cobalt, aluminium, manganese and rare earth contents are extracted. Analyzing the molar concentration shows a purity of the nickel of >99.9% versus the other metals (including potassium) after stage 4. Additional stages can be added to improve the purity without affecting nickel recovery, as can be seen from the approximately constant nickel concentration. The high values in stage 3 for cobalt and manganese are likely due to steady-state not being fully achieved.

The organic phase concentration of the main extraction is shown in Fig. 9. As for the cathode case, the concentration of nickel is constant in stages 2–4 and significantly less in stage 1, indicating crowding. The extraction of metals other than nickel thereby reduces the nickel extraction. Optimizing flow rates to achieve near-saturation of the organic phase can thereby further reduce the extraction of nickel.

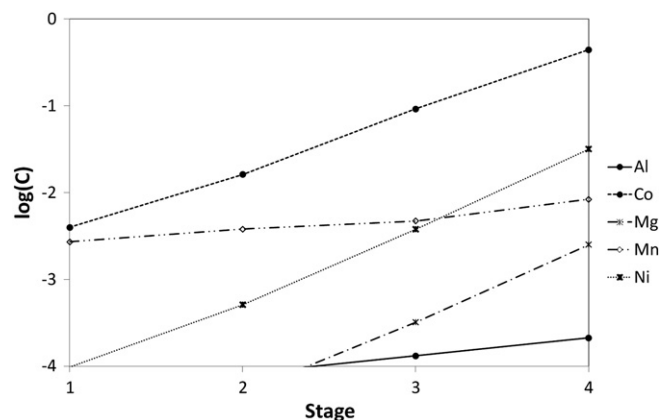


Fig. 6. Aqueous phase molar concentration of the nitrate strip of the organic phase after main step extraction. O:A flow ratio 1:1 and 4 stages. Yttrium content below detection limit.

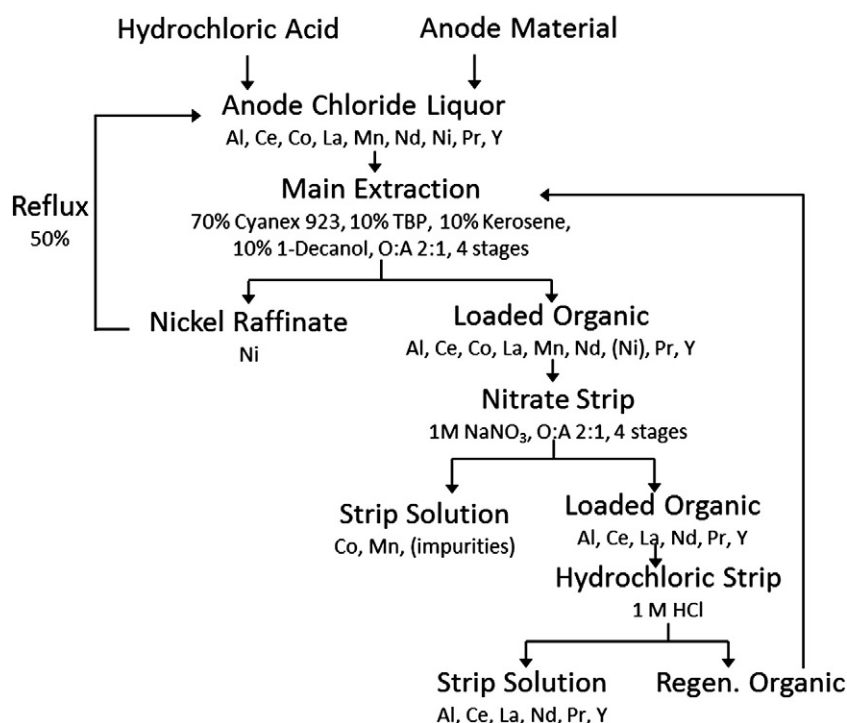


Fig. 7. Process layout for the active anode material process. For each extraction there is an indication of the phase ratio of the flow rates and the number of stages used. Low levels of impurities are indicated in brackets. Potassium is excluded from the layout, since it can be washed off before dissolution.

For the nitrate strip, shown in Fig. 10, a phase volume flow ratio of 2:1 O:A was used to increase water phase concentration. This was unsuitable for the system, and there was insufficient extraction, leading to some stripping of metals other than cobalt and manganese (and residual nickel) in the first organic stage (stage 4).

As can be seen from the lanthanoid-concentration profile, a large amount is stripped in the fourth stage (first organic contact), but only small amounts are stripped in subsequent steps. This indicates that the flow rates were unsuitable in combination with the nitrate concentration, leading to too low a nitrate concentration for extraction of the trivalent content in stage 4. Under optimum conditions only the cobalt, manganese and nickel will strip. This can be seen in stages 1–3 where the stripping of other metals is very low when comparing the organic phase concentration shown in Fig. 11 with the aqueous phase concentration in Fig. 10. The lanthanoid concentration is approximately constant in the organic phase, except for in the first organic stage, showing that the extraction of lanthanoids is high in

the nitrate step. The concentration of nickel is relatively high, and a nickel scrub step should be added before the nitrate strip step. For complete manganese stripping additional steps or other conditions are necessary.

Since a large part of the rare earth content was stripped in the nitrate strip the hydrochloric acid strip was not performed other than as a limited batch experiment whereby the rare earth content was successfully stripped using hydrochloric acid.

4.3. Mixer-settler results for the mixed-material-based leach liquor

With the added knowledge of the first two experiments, some modifications were made to the process layout for the mixed-material flowsheet, shown in Fig. 12. A scrub to remove extracted nickel from the main extraction organic phase was developed and added. A scrub of the organic phase after the nitrate strip step was added to remove the zinc content (and manganese if the nitrate

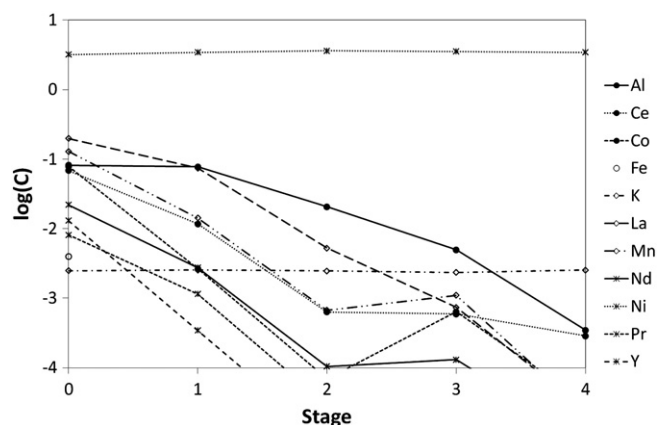


Fig. 8. Aqueous molar concentration for the main extraction step for the leach liquor based on active anode electrode material. Stage 0 is the aqueous phase before entry into the mixer-settler battery. The organic phase is 70% Cyanex 923 (O:A flow ratio 2:1).

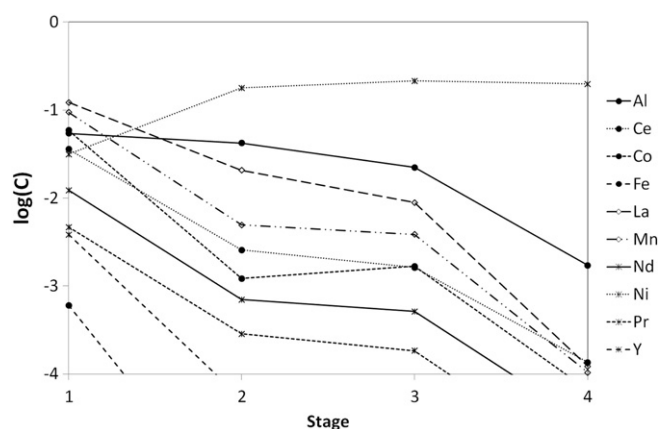


Fig. 9. Organic phase molar concentration for the main extraction step for the leach liquor based on active anode electrode material. The organic phase is 70% Cyanex 923 (O:A flow ratio 2:1).

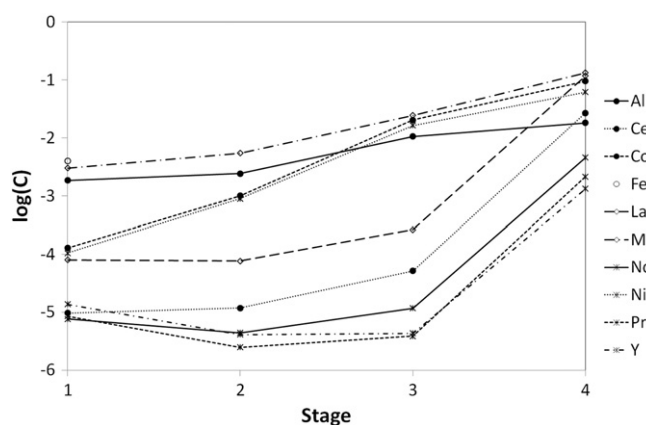


Fig. 10. Aqueous molar concentration for the nitrate strip step for the anode-based system. The aqueous phase is the leach liquor based on active anode electrode material after main extraction, and the organic phase is 70% Cyanex 923 (O:A flow ratio 2:1).

strip step was unsuccessful). The acidity of the nitrate strip was increased to 0.1 M, thereby increasing manganese stripping without unduly affecting the lanthanoid extraction. Pure water was used to strip iron and any residual zinc in the last step.

In the process based on dissolved mixed-electrode material, similarly to the cathode scheme, the iron and zinc can be extracted in a pre-step followed by a main extraction of cobalt, aluminium, manganese, lanthanum, cerium, neodymium, praseodymium and yttrium. However, for this experiment the zinc and iron are extracted with the main extraction, since the pre-step in the cathode process failed to extract iron, and the process layout is modified accordingly. The purified aqueous phase contains nickel, magnesium and potassium. As for the anode case, the cobalt and manganese can be stripped, either together with the trivalent content, using a low chloride concentration strip, or separately, using a nitrate strip.

The aqueous phase concentrations are shown in Fig. 13. The extractable metals are extracted to a very high degree and are below 0.1 mM after stage 3. The potassium, magnesium and nickel concentration remains fairly constant. Molar purity for nickel with respect to the extractable elements (not including potassium and magnesium) after stage 4 is >99.96%. Potassium is practically unaffected through the process, and magnesium behaves similarly to nickel in terms of extraction properties. Additional stages can be added to improve the purity without affecting nickel recovery, as can be seen from the constant nickel concentration.

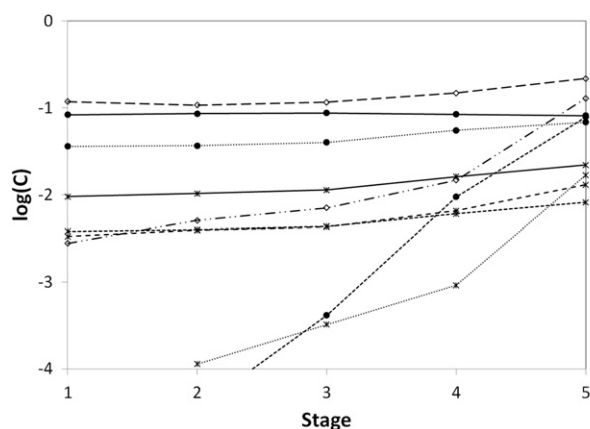


Fig. 11. Organic phase molar concentration for the nitrate strip step for the anode-based system. The aqueous phase is the leach liquor based on active anode electrode material after main extraction, and the organic phase is 70% Cyanex 923 (O:A flow ratio 2:1). Stage 5 is the organic phase concentration before entering the mixer-settler system.

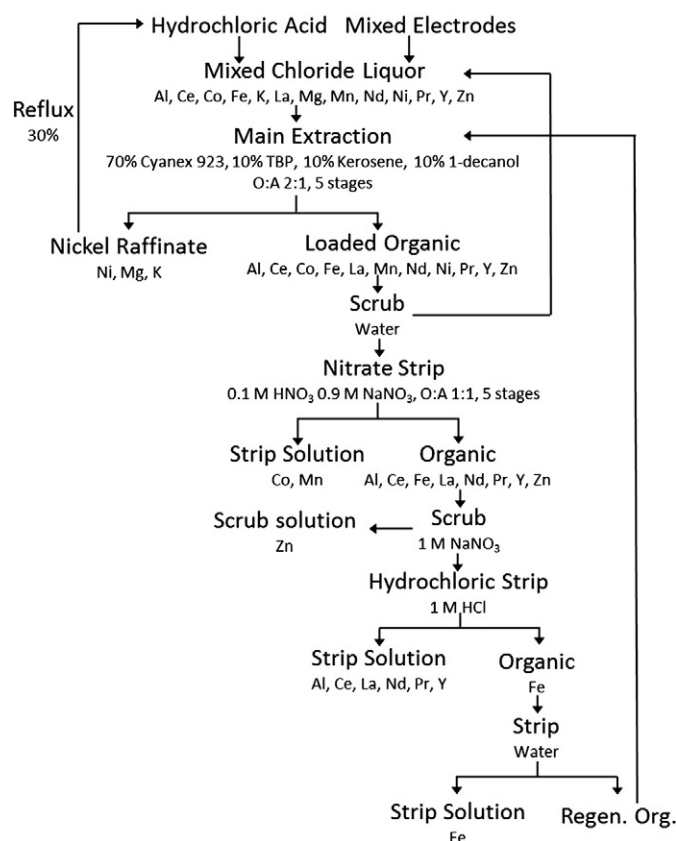


Fig. 12. Process layout for the mixed material process. For each extraction there is an indication of the phase ratio of the flow rates and the number of stages used.

The trend for the organic phase concentration is that a small amount of magnesium and nickel is extracted, with a lower concentration in the last aqueous step due to significant crowding by the more extractable metals, which decreases the concentration of nickel and magnesium. If the extraction of non-nickel content is optimized by means of the reflux level and the phase ratio, the crowding can likely be increased, thereby further reducing the nickel and magnesium extraction. The trend in the organic phase for the metals with higher distribution ratios is increasing to approximately full extraction.

In each stage of the main extraction, the greater extraction in the mixed system than in the anode system is likely related to the higher

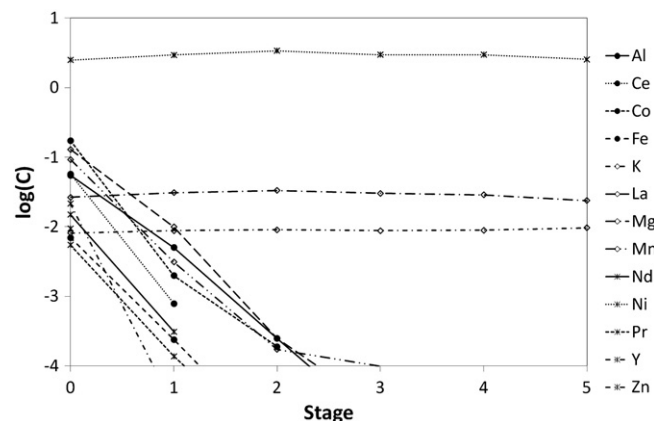


Fig. 13. Aqueous phase concentration, five-stage extraction, stage 0 is the initial aqueous concentration before entry into the system. The concentration falls below detection limits (approximately -4) for the majority of the extractable metals after the second stage. Flow ratio 2.5:1 (O:A).

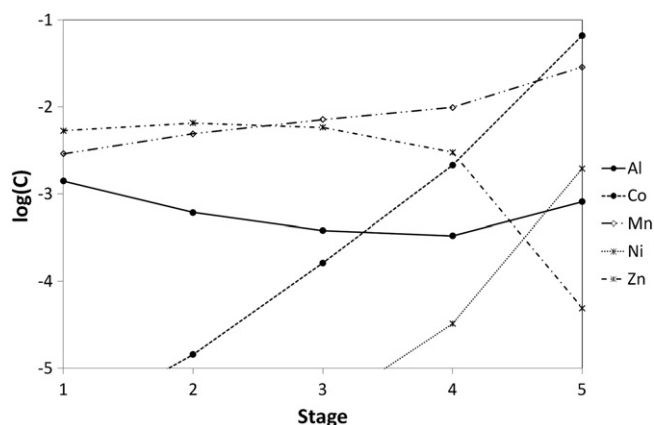


Fig. 14. Aqueous phase concentration of the nitrate strip, five extraction stages. The loaded organic solvent enters the fifth stage and the majority of cobalt and manganese are stripped, flow ratio 1:1 (O:A). The rare earth metal concentrations were below -5 in all stages.

flow ratio in the mixed-material experiment, thereby decreasing loading, or is because the anode system has not fully achieved steady-state.

Since the nickel concentration in the organic phase was significant (though relatively small compared to the aqueous phase concentrations), a three-stage cross-flow scrub step using water was added. The phase volume ratios of the three stages were 25:1, 50:1 and 100:1 (O:A). This removes more than 96% of the nickel content, and more stages can be added to increase the recovery. However, it also reduces the concentration of the other elements. The aqueous scrub is returned to the dissolution step so no material is lost. The efficiency of the process is thereby slightly reduced, but the purity of the cobalt strip phase is increased and a higher degree of nickel can be recovered in the main aqueous nickel stream.

Stripping of cobalt and manganese using 0.1 M nitric acid with 0.9 M sodium nitrate from the nickel-scrubbed organic phase is shown in Fig. 14. The majority of the manganese is stripped but requires additional stages or a scrub of the resulting organic phase or a changed aqueous phase to increase the manganese strip. Additional acidity increases the stripping of manganese, but it also increases the rare earth and aluminium strip.

The zinc concentration in the nitrate strip is high in stages 1–4, indicating that the zinc could be stripped using this aqueous phase. However, it does not strip, since the distribution ratio is high in stage 5, likely due to an elevated chloride concentration. This further indicates that a pre-main zinc extraction step is suitable. The majority of any remaining manganese and zinc were scrubbed using a

five-stage cross-flow scrub step using the same aqueous flow 0.1 M HNO_3 0.9 M NaNO_3 at a phase ratio of 5:1 (O:A).

The rare earth metals were subsequently stripped, using 1 M hydrochloric acid, in a batch cross-flow set-up in order to use a low phase ratio and thereby raise the aqueous concentrations, results shown in Fig. 15. The trivalent metals were stripped relatively efficiently, though the resulting concentrations were low.

The last step of purification of the organic phase to remove iron with pure water required several stages to remove the very low iron content. Improving the pre-main step treatment to remove iron and zinc before the main step would improve the process efficiency.

5. Discussion

The major difference between the three processes is the difference in composition between the separated metal streams. The nickel stream from the anode-based process can be devoid of potassium and magnesium, whilst the cathode- and mixed-based processes contain both potassium and magnesium. If at the refining stage electro-winning is used this is not a major problem, since magnesium and potassium should not electrodeposit.

For the nitrate strip separation the cobalt and manganese stream is similar for all the processes, except that the cathode has low amounts of manganese and the anode has high amounts compared to the amount of cobalt.

The advantages of using the separated electrode materials are the initial separation of metals and the increased concentration of the extracted metals, since mixing a larger number of metals dilutes individual concentrations. The advantages of a mixed-material process are the increased ease of handling the feed material and the fact that it could likely be optimized to function without reflux.

It is probable that all three processes could be used in a single plant at different times, depending on the available feed material, since the only major difference in the main step will be an optimization of reflux levels, as the same number of stages can be used in each process.

6. Conclusions

Process layouts for three different waste mixtures from nickel metal hydride batteries were tested in mixer-settlers. The initial step, involving four or more stages, extracts the extractable metals and successfully creates an aqueous phase of purified nickel for the three systems. The separations achieved during the strip, removing cobalt and manganese from the trivalent content using a nitrate solution, constitute an option. Adding a scrub step for the organic phase after the main extraction improves the nickel recovery and raises the purity of the subsequent strip streams.

Interesting points for future research include investigating solvent losses, chloride and nitrate concentrations in each stage, optimization of strip and scrub steps and improving the pre-main extraction of zinc and iron.

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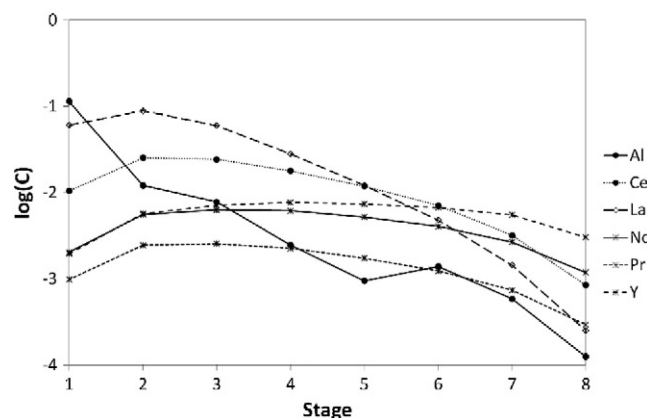


Fig. 15. Aqueous phase concentration of a batch cross-flow 1 M hydrochloric acid strip on the zinc-scrubbed organic phase after cobalt and manganese strip. Phase volume ratio 10:1 (O:A) in all stages.

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